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THE CHARACTERISTICS OF DISTANT COMETS

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SUMMARY

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An analysis of spectroscopic observations and colors of comets with heliocentric distances greater than 3.5 AU indicates that only sunlight scattered from solid grains can explain the data. The orientation and curvature found by Osterbrock in two comets are consistent with Bessel-Bredichin theory of comet tails. Because of these characteristics, Brandt's use of these comet tails to study the interplanetary medium is not valid.

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INTRODUCTION

The tails of two distant comets were observed and analyzed by Osterbrock (Reference 1). He found the tails to be intermediate between the radial direction from the sun and the tangent to the comet's orbit. In his analysis, Osterbrock concluded that this result must have come about through the combined action of the repulsive force of radiation pressure and the resistive force of interplanetary matter. Interplanetary material was assumed to be at rest (relative to the sun) and to have a density of 20 protons/cm³. Under these conditions, he calculated the behavior of possible components of the tails, and concluded that only the diatomic hydrides CH, OH, or NH, or grains that are small compared to the wavelength of visible light would satisfy the tail observations. Radial tails were predicted for C₂, CN, or dust comparable in size with the visible wavelengths.

Although comet observations are not sufficiently complete to yield a definitive model of comet behavior, they are very extensive. Many significant and suggestive observations are scattered throughout the literature pertaining to comets, as in the reviews by Bobrovnikoff, Richter, and Swings (References 2, 3 and 4) and current announcements. Although a comprehensive study and digest of all this information would be of great value in a theoretical study of comet phenomena, a true understanding of comets should be based on and should explain the myriad variations of comet behavior. Such an approach is not yet possible—nor, at this stage, desirable.

A more restricted attempt, based on certain generalizations concerning comet phenomena, shows that the conclusions reached by Osterbrock to be inconsistent with the major kinematic and spectroscopic features of comets. The most favored theory is that the luminosity of distant comets arises almost exclusively from a dust-scattered solar continuum, and no resistive force seems necessary.

Osterbrock's conclusions concerning the interaction of the components of distant tails were subsequently used by Brandt (Reference 5) to examine theories of interplanetary matter by Chamberlain and Parker (References 6 and 7). Brandt proposed that Chamberlain's theory was in agreement

* This report has been published in substantially the same form in *Annales d'Astrophysique*, 25(5), September-October 1962.

with observations, whereas a large discrepancy occurred when Parker's solar wind concept was applied to comet tails. As will be shown in the present note, the comet tail model adopted by Brandt is not valid; and the analysis he attempted cannot be applied to the interplanetary medium. Consequently, no choice between theories of that medium can be made at present on the basis of distant comet observations.

The possible use of comets as solar system probes has been pointed out on several occasions; unfortunately, as has also been pointed out, present knowledge of comets is too incomplete for this possibility to be realized.

COMPOSITION

Spectroscopic observations of comets beyond 3 AU show a continuum only. In most instances this is definitely a scattered solar continuum (References 8 and 9). The first spectra of Halley's Comet in 1909 (Reference 10) were predominantly continuous, with possibly a trace of emission. Walker's observation of Comet Baade, 1954h, at 4 AU fell in the interval covered by Osterbrock's observations and showed no trace of emission. It is doubly significant in that it is the most distant spectrum of a normal comet and also that the findings contradict the proposal that the visible components are diatomic hydrides.

The remaining distant spectra were of the comet Schwassmann-Wachmann II during active periods, and all showed a reflected solar continuum only.

The following analysis shows that the coma and tail luminosity of Comet Baade cannot be explained as being due to molecular emissions too weak to have been spectrographically detected by Walker. In particular, the diatomic hydrides could not have contributed to the yellow or red photographs, or to the visual photoelectric measurements. A dust-scattered solar continuum would fit these observations; and it is completely consistent with all spectroscopic observations of distant comets, and particularly with that of Comet Baade by Walker.

Osterbrock remarked that blue, yellow or red images of Comet Baade, taken within a few days of each other, did not show any marked differences. Furthermore, Walker's three-color photoelectric measurements (Reference 9) gave a B-V color index of +0.80, slightly redder than for the sun ($B-V = 0.64$). The intensity of light in the comet's spectrum conforms closely to the expected intensity of sunlight scattered by particles a few tenths of a micron in size. For the three simple hydrides suggested by Osterbrock, all emissions are below 4300Å. These would not show with red or yellow filters, and consequently could not have been the source of light in the coma or tail photographs.

Cometary spectra have been reviewed by Swings (Reference 4) and by Swings and Haser (Reference 8). The species CH, NH, and OH can be identified only a little beyond 1.5 AU and their presence at 4 AU would not be expected. All ionized molecules fade out between 1.5 and 2 AU.

The principle emission features of comets are associated with CN and C_2 . The former are all less than 4300Å, except for the red CN system which would not show on Osterbrock's plates. CN has

been detected at the greatest distance from the sun, but disappears at about 3 AU. The Swan bands of C_2 in comets occur only in the region from 4700 to 5450A with appreciable intensity, and they would contribute to the yellow image but would be negligible for the red. The C_2 emission tends to fade out somewhat before CN.

Two other neutral constituents have been identified. The "4050" bands of C_3 are an important feature, appearing in the blue only, and visible to nearly 3 AU. NH_2 is associated with a series of strong bands between 6000 and 6600A, but weaker bands extending to 4200A may also be produced by NH_2 ; these emissions disappear at about the same distance as C_3 .

A combination of CN, C_2 , C_3 and NH_2 could account for blue, yellow and red images. However, these molecules do not behave alike with respect to extension into the head (References 4 and 8), and the photographic images would differ. Neither does it seem too likely that they could be combined to give the U-B and B-V color indices found by Walker.

Not only do the ionic species (mainly CO^+ and N_2^+) disappear at distances between 1 and 1.5 AU but the tails they produce are long and narrow. The bands of these ions are also predominantly in the blue region (References 11 and 12).

It seems certain that the direct photographs of Comet Baade could not have been produced by the known cometary emissions.

Osterbrock suggested that the tail could be composed of dust with a scattering cross section reduced by a factor of 10^4 from that for micron diameter particles. If this were the case, the scattered light would be much more intense at short wavelengths than is shown by the spectra or color measurements. Swings (Reference 13) pointed out that dust particles in the head and in the tail may be of different dimensions. However, the light scattered by tail particles is not blue, as would be the case for very small grains (Reference 14).

The spectroscopic evidence supports the conclusion that the observed component of distant tails is dust with dimensions of the order of the wavelength.

In his latest paper on the use of comet tails as probes of interplanetary space, Brandt (Reference 15) compares the deviation of tails from the radial direction for heliocentric distances less than and greater than 2 AU. Straight tails within 2 AU are considered to be composed of molecular ions (primarily CO^+) whereas in this section, we have concluded, that beyond about 2 AU the dominant or sole constituent is dust. Therefore, Brandt's model for the velocity and density variation of interplanetary gas depends upon an invalid argument. It would be more appropriate to consider why the apparent composition of comets changes so markedly, since this may be related to the environment of the comet.

STRUCTURAL FEATURES-KINEMATICS AND DYNAMICS

The other major conclusion reached by Osterbrock, and adopted by Brandt, was the necessity of a resistive force acting on the material composing the tail. It appears to be no more necessary to

introduce a resisting medium as an explanation of the shapes of distant comet tails than for those near the sun.

The study of comet forms (Reference 16) shows that tails having a continuous spectrum deviate considerably from the prolonged radius vector in the direction opposite to the motion of the nucleus. For these tails, relative repulsive forces are found to be nearly unity. Therefore, near the sun, tails with continuous spectra behave exactly as at greater distances.

For Comets Baade and Mrkos, tails 3 to 8 minutes of arc in length are or the order of 10^6 km long. Using an average expansion velocity of 0.5 km/sec (Reference 16), we obtain an interval of about 20 days as being necessary to form the tail. For the angle ϕ between the radial direction and the line to the end point of the central line of the tail, the expression from Bessel's theory, as given by Wurm (Reference 17), becomes

$$\tan \phi = \frac{2(2p)^{1/2} \xi^{1/2}}{3r(1 - \mu)^{1/2}} \quad (1)$$

Here, $p = 2q$ is the parameter of the orbit, μ is the ratio of the repulsive force to solar attraction, and ξ is the radial extent of the tail. According to Osterbrock's analysis, the radial and tangential components of the tails are about equal. The ξ component is then about 0.01 AU and by inserting values for all quantities except $(1 - \mu)^{1/2}$ into Equation 1, we have

$$\tan \phi = \frac{0.07}{(1 - \mu)^{1/2}} \quad (2)$$

A value of $\mu = 0.99$ fits Osterbrock's results. The calculation of the position angle of the tail of Comet Humason (1961e) at 5.2 AU by Guigay* supports this result.

Osterbrock reported that the tails usually had a slight curvature. This feature can also be explained by standard comet-tail theory because of the geometry of the situation which Osterbrock commented on in a different respect. For the tails studied by Osterbrock the angle between the orbit plane and the plane of the sky through the comet was 75° at its minimum and grew to 90° where the earth crossed the nodal line. The forshortening factor fell between $1/4$ and 0 for the radial component; the perpendicular component, on the other hand, always lay almost at right angles to the line of sight (with a forshortening between about $3/4$ and 1).

Figure 1 shows the shape of a tail inclined 45° to the radial direction from the sun as in Equation 2. The dashed curve—the projected tail seen from the earth with approximately the minimum distortion expected—was obtained by forshortening the ξ component by a factor of $1/3$. Since the average tail has less curvature than the projected tail of Figure 1, we may expect to observe tails with only slight curvature.

In addition to the projection effects, two other factors must be considered: variations of μ ; and ejection of matter from the nucleus over a range of angles. When all these factors are taken into account, the problem of the shape and orientation of tails of distant comets does not appear to differ

*G. Guigay as reported by Ch. Fehrenbach in Circulaire No. 1782, Union Astronomique Internationale, Bureau Central des Télégrammes Astronomiques, Observatory Copenhagen, November 25, 1961.

from that of nearby comets. In particular, the introduction of a resistive force is no longer necessary.

It is possible that at 4 AU comet tails are different, but the scanty data available does not indicate such to be the case.

In addition to the coma and tail, the variety of cometary features include transient phenomena such as halos, fans, jets and envelopes (Reference 16). All these phenomena are associated with the head of a comet. With the exception of the flaires or halos of Comet Schwassmann-Wachmann II (occurring between 5.5 and 7 AU), these events are generally limited between 0.5 and 1.5 AU. Although not characteristic of distant comets, the flares do explain something of the behavior of the molecular species which bear on Osterbrock's analysis.

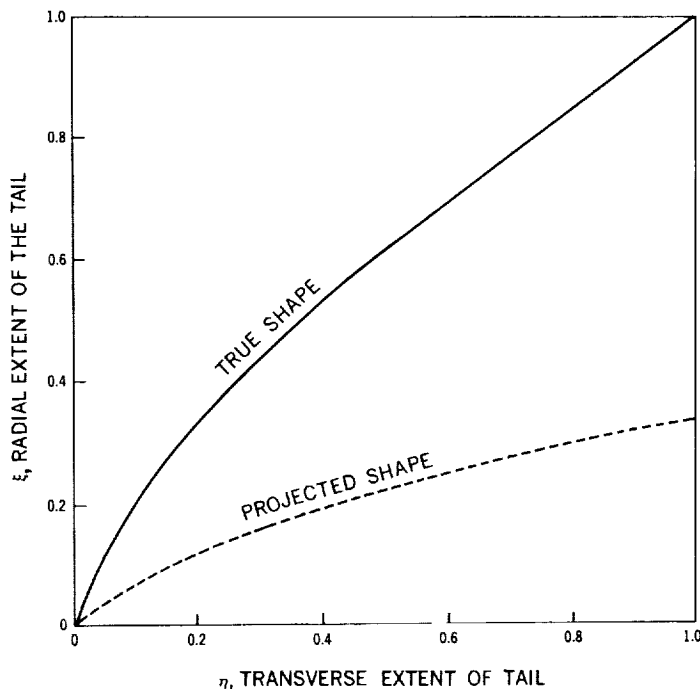


Figure 1—Predicted shape of tail.

At 1 AU, CN and C_2 halos maintain their spherical shape for several days (References 2, 10 and 16), and as Wurm (Reference 18) points out, this requires that the repulsive force on these molecules be very small. The generally circular intensity contours for C_2 and CN in the coma (Reference 19) further support this conclusion. The behavior of C_2 and CN near the sun contradicts Osterbrock's calculations which indicated a strong repulsive force from radiation pressure at 4 AU. The source of this discrepancy is not clear.

THEORETICAL CONSIDERATIONS

The preceding discussion of the limited data on spectra and colors of distant comets confirms the prevailing opinion that only scattering from solid grains is observed at great distances. Bobrovnikoff (Reference 16) reported visual observations of three bands, corresponding in position and brightness with the C_2 Swan bands in Comet 1927 IV (Stearns) at 3.7 AU. This appears to be the greatest distance at which cometary molecules have been observed. How can the failure to detect gas beyond 3 or 4 AU be explained when no mechanism for ejecting only solid particles from the nucleus can be devised?

We cannot conclude that no gas is present at great distances, for the observations are not nearly complete or sufficiently sensitive, but there seems to be no question that the observable ratio of dust to gas becomes very large. The very low relative intensity of the emission (when the comet has

receded) requires a reduction in the relative density of luminous molecules of nonflaring comets, for which the coma is in a quasi-steady state. The situation during a flare, when again only dust is detected, may be different because of the short duration of the outburst.

Oort and Schmidt (Reference 21) have presented evidence for a greater dust concentration in their "new" comets, i.e., those having made only one or two near solar passes. A very old comet, such as Comet Encke, has a nearly pure emission spectrum. By dividing comets into four groups, according to age, they found some indication that older comets possessing stronger emission also show a stronger brightness variation with solar distance r . The luminosity of new comets varied on the average as $r^{-2.8}$, whereas for old periodic comets the luminosity variation was $r^{-4.2}$.

Comet emission luminosity usually is attributed to vaporization and excitation of gases by solar radiation (Reference 16). Similarly, the intensity of the solar scattered continuum depends upon ejection of grains and scattering of incident light. Each of the two factors for bands or continuum varies as r^{-2} , and the resultant intensity ideally goes as r^{-4} . Observations yield an average exponent somewhat less than 4; Bobrovnikoff (Reference 2) obtained a value of 3.3 for all comets without regard to spectra.

The formation of emission bands actually involves three processes. In addition to vaporation and excitation, a step involving the production of the observed radicals from stable parent species is required. The photodissociation process introduces another factor of r^{-2} , causing the theoretical emission luminosity to vary as r^{-6} .

Observationally and theoretically the emission luminosity varies more rapidly than the continuum luminosity by a factor r^{-2} . This corresponds to a ratio of 16 as the comet goes from 1 to 4 AU and would significantly contribute to the earlier disappearance of the emission spectrum.

A discrepancy between the observed and theoretical luminosity variations by a factor of roughly r^2 exists for both the emission and continuum spectrum. This casts considerably uncertainty on the validity of this interpretation and poses a problem for interpretations of comet luminosity in general. Without, however, more complete observational data, including photometric studies of emission bands and continua over much greater ranges of distances than are currently available, one cannot say how real the discrepancy is.

We may say, however, that there is a definite decrease of the emission spectrum at a more rapid rate than for the continuum. No conclusions can be reached until systematic observational studies of distant comets have shown what effects require explanation.

Until further progress has been made, the use of comets as solar system probes will remain very restricted, and conclusions derived thereby will remain uncertain.

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